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Blink Rate As a Measure of Fatigue: A Review

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16. Abstract

Fatigue is one of many factors that can impact the ability of pilots and air traffic controllers (ATCs) to maintain their performance across time. This review of the literature is an outgrowth of a study concerning the relationship between several gaze measures and time-on-task (TOT) performance of subjects on an ATC monitoring task. Blink rate is one of several psychophysiological measures that has been proposed to assess fatigue associated with TOT. The acrimonious debate between Luckiesh and Tinker and Bitterman is evaluated and that portion of Luckiesh's results dealing with increases in blink rate as a function of TOT is well substantiated by the results of most other investigations. Some evidence is presented that variables, other than TOT, also affect blink rate, as well as data suggesting that the nature of the blink (blink closure duration) may be affected by TOT effects. The development of improved methodologies for detecting attentional lapses or the impaired ability of operators to perform on perceptually and cognitively demanding tasks will allow us to conduct improved evaluations of the effectiveness of various fatigue countermeasures.

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Blink Rate As A Measure Of Fatigue: A Review

INTRODUCTION

Variability in blink rate excited only sporadic interest until Ponder and Kennedy (1927) undertook their thorough investigation of the phenomenon. It had been tacitly accepted that blinking served the sole and immediate physiological need of the ocular system, namely lubricating and cleansing the corneal surface. These investigations were designed to test whether these commonly accepted physiological reasons for blinking were not only necessary but also sufficient to account for blinking behavior. They clearly demonstrated that the latter was not the case, that many blinks were controlled by the central nervous system rather than peripheral processes. They concluded that for this periodic, spontaneous blink, "the rate of blinking is closely related to 'mental tension' of the subject at the time, and that in all probability the movements constitute a kind of relief mechanism whereby nervous energy, otherwise unutilized, passes into a highly facilitated path" (p 110).

It is of more than passing interest that observations on blinking in infants had demonstrated infrequent blinking, though the mechanism for blinking is well established at birth. Thus, the idea that the major reason for blinking is cleansing and lubrication of the cornea could have been questioned many years earlier. The finding that blink frequency steadily increases from the first year of life casts further doubt on theories that stipulate lubrication and cleansing as sole or major determinants of blinking. Further, Ponder and Kennedy's observations on blink frequency of subjects in humid and arid environments demonstrated little difference in blink rate under these conditions. One would have expected a markedly higher blink rate in the arid as compared to the humid environment. Thus, drying of the corneal surface does not appear to be a major determinant of blinking. We need to blink relatively infrequently to maintain a film of fluid over the cornea.

We do not wish to suggest that lubrication and cleansing are not determinants of blinking, rather that, in man, they do not appear to be sufficient to account for the amount of blinking done by young adults. As documented by Ponder and Kennedy (1927), people do blink more frequently when exposed to an environment high in air particulates, such as those associated with cigarette smoking.

Why then, do we blink as frequently as we do? Ponder and Kennedy suggested that it may be a mechanism for relieving nervous tension. This possibility is one that, with minor modifications, has been suggested by a number of authors. Meyer (1953) and Meyer, Bahrick and Fitts (1953), for example, have suggested that blinking involves efferent neural interactions between brain mechanisms responsible for the muscles controlling the eye lids and other muscle groups. Their formulation is not far removed from the Pavlovian notions of "foci of irradiation," viz., the spread of excitation from activated brain centers adjacent to those that control blinking. It is also comparable to current notions in cognitive psychology. The literature on priming, for example, suggests that priming effects may be accounted for by the spread of excitation from an activated node in the CNS (to be read as conceptual and not central nervous system) to adjacent nodes associated with the activated node by prior experience (Collins & Loftus, 1975) and (Collins & Quillian, 1976).

These are interesting "notions" to account for blinking. They, unfortunately, cannot be directly tested, nor is what we know about blinking terribly supportive of such theorizing. If "spread of excitation" (Meyer, 1953) accounts for blinking, and if myelinization is a major factor in the reduction of such "overflow" phenomena, then we should find that young children, rather than blinking less frequently than adults, should blink more frequently. The facts indicate quite the opposite. Young children blink significantly less frequently than older children and adults. In fact, both spontaneous as well as reflex blinks occur relatively infrequently in infants younger than 2 months of age (Conrad, 1955) and (Lohr, 1960).

Psychologists, some physiologists and ergonomists have been less concerned with physical and environmental factors responsible for the act of blinking and more concerned with psychological or behavioral variables that may affect blink rate. One such factor is "fatigue." Fatigue is difficult to define. One way to operationally do so is to express it in terms of time-on-task (TOT) effects.

One of the earliest "studies" attempting to relate blink rate to eye fatigue was conducted by Katz (1895), using himself as subject. Katz recorded his blinks using a Marey capsule with a string attached to the outer angle of the orbital muscle. He made 3 sets of observations under different levels of light intensity. The 3 levels of light intensity utilized an Edison glow light, an open gas flame, and a low intensity light which made reading difficult. In all 3 conditions, blink rate increased from the first to the second 5 minutes of reading. He also reported that the lower light intensities led to more frequent blinking, even during the initial 5 minutes of reading. Katz concluded that blink frequency was a reasonable measure of ocular fatigue. During the 1930s and 1940s a major attempt at linking aspects of blinking to fatigue was undertaken by Luckiesh and Moss (1937, 1942, 1944). Their major purpose, as lighting engineers, was the development of a metric that would provide objective data on "the expenditure of human energy in seeing." Their experiments demonstrated that the performance of tasks involving visual activity produced effects considered to be of central origin, on muscle tension and heart rate. Ponder and Kennedy's conclusions, therefore, suggested to them that the eyeblink might prove to be useful as an objective measure of the degree of tension or state of ocular fatigue of the subject. This position had been suggested earlier by Katz (1895), Buettger (1923), and others. Litinski (1934), for example, had proposed the recording of "winking" as a method for the study of ocular fatigue associated with reading in children.

A great deal of work was done by Luckiesh and collaborators in testing the rate of blinking as a measure of "visual fatigue." They recorded blinking (observationally) under a number of experimental conditions:

1. during the first and last 5 minutes of 1 hour of continuous reading;
2. during reading of different type size, again for extended time periods;
3. during reading with and without glare;
4. during the performance of visual tasks requiring rapid alternate fixation of 2 different test objects (specifically letters); and
5. during reading while wearing eye glasses with incorrect refraction.

Their general conclusion was that "the rate of blinking is increased without exception when the specific visual task is made more difficult or more prolonged. However, this generalization may not be extended to include various types of visual tasks; that is, the reflex blink is not necessarily an adequate criterion for comparing 2 tasks which are radically different in character. For example, the visual task required in ... (rapid alternate fixation) is introspectively more severe than that required in ... reading 12-point type, yet the actual rate of blinking is slower in alternate fixations."(Luckiesh & Moss, 1937, p. 224-225).

This team of researchers conducted studies utilizing blink frequency as the dependent measure over more than a decade. During that time there was a subtle change in terminology. Rather than speaking of blinking as a measure of "ocular fatigue," they later related changes in blink frequency to concepts such as "ease of seeing" and "readability." They, nevertheless, continued to espouse the position that, "it is axiomatic that fatigue increases with the duration of the task, it follows ... that the rate of blinking is a function of the duration of the task and a measure of the fatigue induced by performing the task" (Luckiesh and Moss, 1937, p. 225).

In 1942, Luckiesh and Moss published *Reading as a Visual Task*. This book was scathingly reviewed by M.A. Tinker (1943). He questioned the idea that either rate of blinking or heart rate were valid measures of readability. Tinker, at that time, favored speed of reading as the measure of readability and based recommendations for type-size and illumination on his studies using this measure (Patterson &

Tinker, 1940). Luckiesh and Moss had taken the position that a performance index is insufficiently sensitive to evaluate either fatigue or "conditions of work," i.e., lighting conditions. Tinker's review initiated serious controversy about the validity of blink rate as a criterion for readability. This controversy dominated the literature for a number of years and was, we believe, the major contributor to the subsequent lack of interest of psychologists and ergonomists in considering the spontaneous or periodic blink as a measure of anything, even though elicited or reflex blinks retained their popularity in psychological research on conditioning (Mauk & Thompson, 1987).

Tinker and Bitterman (1945) were the major critics of Luckiesh and collaborators. What was the basis for the differences in empirical results obtained by these investigators? Luckiesh required subjects to read text for 1 hour under conditions he described as "continuously and natural." The text was selected for its uniformity of interest and for its low and uniform emotional valence. Subjects were not required to perform any operation other than "natural reading," which involved holding the book they were reading and turning pages as they finished reading a page of text. Blinks were counted by a trained observer for 5-minute periods at the beginning and end of an hour of reading. All of the variables studied by these authors (illumination, type-size, glare, ocular correction) were examined separately.

Tinker, in his 1943 review, considered this design to be lacking in experimental rigor in that it used non-standardized reading material, failed to check on subjects' comprehension, and instructed subjects to read at their "natural rate." Bitterman (1945) and Bitterman and Solway (1946) joined the debate with 2 studies employing continuous recordings of (what was identified as) electromyographically recorded eye lid activity, as well as heart rate. Bitterman concluded that his results did not support the value of either heart rate or blink rate as indices of visual efficiency. Bitterman focused on type size and dealt with recordings for only short time periods, though each experimental run took approximately 50 minutes. He utilized the Minnesota Vocational Test for Clerical Workers, which required subjects to check paired names and number groups for identity or non-identity. The task involved putting a plus or minus sign next to the pairs. Subjects worked for two 15-minute periods interrupted by a 10-minute rest period. They performed this task on 2 days. Evaluating blinks for successive 5-minute periods Bitterman found a significant difference in rate between the first and second 5-minute period, but the first 5-minute period was not significantly different from the last 5-minute period. Luckiesh (1946 comment) suggested that the results of the Bitterman experiment, consisting of discontinuous reading punctuated by manual operations, could not be compared to the results of his studies, in which subjects read with as little interruption as possible and for longer periods of time.

Bitterman and Solway's experiment (1946) more nearly resembled Luckiesh's task. Subjects read text for a 40-minute period on each of 2 successive days. Illumination level was manipulated as a between-days variable. Mean blink frequencies were plotted for successive 5-minute periods. Individual curves for all 10 subjects were included in the report. There was considerable variability in blinking, both within, as well as between subjects. The highest blink rate for an infrequent blinker was 6 blinks per minute, while the lowest rates for 3 frequent blinkers were 12, 20, and 22 blinks, respectively. Excluding these frequent blinkers from analysis, one finds that the range of maximum blink rate for the remaining 7 subjects ranges from about 6 to 10 blinks per minute. Using Luckiesh's procedure of comparing blink rate during the initial 5 minutes of task performance to the last 5 minutes (in this experiment, minutes 1-5 vs. minutes 35-40), we find that 5 of the 7 subjects who cluster together in average blink rate show the pattern of increasing blink rates from the early to the late period. Two subjects demonstrated a decrease. Of the 3 with higher blink rates, 2 demonstrated the pattern of increasing blink rate. Thus, 7 of the 10 subjects demonstrate the pattern identified by Luckiesh. Bitterman did conclude that, though the effect was not statistically reliable, there was a tendency for an increase in blink frequency across task performance, regardless of illumination level (the other variable manipulated). There

were further published comments by Bitterman and Luckiesh with, of course, neither convincing the other of the validity of his position.

McFarland, Holway, and Hurvich (1942) present some mixed results with respect to blink rate as a measure of fatigue. They, like Luckiesh, used an observer to surreptitiously count blinks, and had subjects read text with no comprehension testing. Their first study utilized only 3 subjects who read for 1 hour under each of 3 levels of illumination (0.5, 15, and 650 foot candles). A consistent increase in blink rate over time was demonstrated for only 1 subject, and no reliable effects of manipulating light intensity was obtained. A second experiment utilized 6 subjects reading hard copy, hard copy placed on a microfilm stand, and microfilm. Each subject read for 1 hour under each of the 3 conditions. Five of the 6 demonstrated the expected increase in blink rate under both the book and the microbook reading conditions, and 3 of the 6 under the microfilm condition. No statistical analyses of data were presented. These authors were satisfied to present means and standard deviations. A third study, one not involving reading, utilized 11 subjects with the requirement to shift gaze between 2 flashing neon lights that were 25 degrees apart. Rate of light alternation was 90 per minute and flash duration was 0.1 seconds. Subjects performed this task for 15 minutes. Blink rate increased for each subject from the first to the second, and to the third 5-minute period of task performance. Excluding 2 subjects who had unusually high blink rates, these authors reported that their results were in agreement with those published by Luckiesh and Moss.

Having obtained results comparable to those of Luckiesh and Moss, they took the next step of evaluating blink rate in the morning (between 9:00 and 9:30 AM) and late afternoon (between 4:30 and 5:00 PM). Data were collected on 16 office workers for 7 minutes each, at the previously mentioned times. Data are reported for 15 subjects. Eleven showed an increase in blinking from the AM to the PM condition, 1 showed no change, while 3 demonstrated a decrease. Two of the subjects demonstrating a decrease had the highest AM blink rates of the group.

McFarland et al. (1942) refer to an unpublished study by R.L. Thorndike, who studied blink rates at the beginning and end of the working day in 6 typesetters. His major conclusion was that "under the condition of these observations, the blink rate was about as likely to decrease as to increase after a day's work of reading or revising proof" (p. 81). McFarland et al. came to the conclusion that "The rate of blinking can hardly be considered as a valid index of visual fatigue" (p. 86).

The rest of the McFarland et al. report deals with the impact of instructed blinking on some aspects of visual acuity. This paper is frequently quoted by Tinker, as well as Bitterman, as providing conclusive evidence against Luckiesh' claims. Luckiesh apparently read the McFarland report and commented on the small sample size used in the studies on fatigue. It is interesting that Tinker took Luckiesh to task for presenting results of experiments where the sample size was only 10, and not once mentioned the sample size in the McFarland et al. studies. Though we do not wish to appear unkind in our evaluation of the McFarland et al. paper published by the Graduate School of Business Administration at Harvard University, it probably would not have been accepted for publication by a psychological journal, since it contained no statistical evaluation of results but many conclusions.

One further study demonstrating "No fatigue effects on blink rate" (the title of the paper) by Kim, Zangemeister, and Stark (1984) reported, "There was no change in blink rate during 1-hour experiments even though subjects complained of severe fatigue" (p. 337). The reason for the lack of change is readily apparent. It is true that subjects read for 60 minutes, but that 60-minute period was interrupted by rest periods of 1 minute after each 5 minutes of reading. The lack of significant results is reminiscent of the Tinker, as well as the Carmichael and Dearborn (1947) studies (reviewed below), in which comprehension tests were interposed between periods of reading. They also reported no changes in blink rate.

We will now turn to studies with positive TOT effects. Hoffman (1946) had 30 college students read text steadily for 4 hours. Blinks were counted for each

5-minute period from electro-oculographic records. He reported significant TOT effects, with a significant increase in blink rate over time. Blinks increased significantly after the first hour of reading and increased in a steady, though irregular, pattern across the 4-hour period.

Carmichael and Dearborn (1947) had subjects read text for a 6-hour period each. No significant increases in blink rate were obtained for college or high school students reading both easy and difficult text in hard copy or microfilm format. These authors compared the results of their study to Hoffman's (1946), who had used the same equipment in a 4-hour reading session. As described above Hoffman found significant TOT effects for blink rate. The major difference between these 2 studies was that Carmichael and Dearborn had used tests of comprehension at approximately 20-25 page intervals of reading (roughly every half hour reading was interrupted for a test of comprehension), and students were instructed and motivated to read for comprehension. Carmichael and Dearborn came to the conclusion that well motivated subjects do not demonstrate alterations in blink rate as a function of TOT. Hoffman, on the other hand, did not utilize tests of comprehension, the reading material used was conceptually less difficult, students were paid less for their participation, and were not exhorted to do well. He essentially utilized reading procedures similar to those used by Luckiesh and collaborators and obtained comparable results.

It is our suspicion that an analysis of variance, the statistic used by Hoffman, might well have demonstrated significant increases in blink rate as a function of TOT in the Carmichael and Dearborn data. We suspect that the statistical technique used, namely critical ratios, was overly sensitive to the large individual differences in blink rate normally observed between subjects. Carmichael and Dearborn, fortunately, present some of their summary statistics (for individuals) in tabular form. Using their table, we compared blink rate at the start of the experiment with blink rate at 1-hour intervals. There were 6 such comparisons for all reading "events" (easy and difficult text; hard copy vs. microfilm; high school and college subjects) resulting in the calculation of 2x2x2x6=48 ratios. Forty of these ratios were positive and 8 negative (negative indicates that blink rate at the later point in time was lower than at the initiation of reading). Had there been no systematic (or significant) effect, half of the 48 values should have been positive and half negative. The likelihood of finding 40 positive is a chance event less than 0.01. We thus come to the conclusion that Carmichael and Dearborn's data demonstrate a TOT effect. The average increase across all trial blocks was 14% while the average decrease for the 8 negative values was 1.6%.

Though not stated, we suspect that Carmichael & Dearborn sampled blink rate not at exactly 30-minute intervals, as reported, but during the 5-minute period of reading immediately following or preceding each of the comprehension tests. This might well lead to a smaller increase in blink rate than that reported by Hoffman. Ponder and Kennedy (1927) had demonstrated that any interruption or change in task performance could lead to an alteration in blink rate, and Luckiesh repeated this same warning in most of his published papers, especially his comments on Tinker and Bitterman's studies. We will later point out that blink rate is affected not only by TOT effects, but other variables as well. The point we wish to make here is that Carmichael and Dearborn's suggestion that blink rate does not change when subjects are highly motivated can be questioned not only on the basis of their statistical analysis, but also because a number of other variables were manipulated in their study that had not been manipulated in the Hoffman study. We suggest that the major reason for the rather modest increase in blink rate obtained in their study has more to do with the mechanics of interrupting the reading process by the administration of comprehension tests, than by motivating instructions and greater rewards. Perhaps, one of the reasons for the lack of significant effects, or only modest effects, found by Tinker in his studies of blink rate as a function of TOT can be attributed to the fact that he also interposed comprehension tests between segments of reading. Bitterman (1945), in his first study (where the task involved checking whether pairs of stimuli were the same or different) required subjects to interrupt their proofreading and make a decision after each pair

of words by marking yes or no on the paper. This, too, produces interruption in the reading process that could account for his nonsignificant results. Luckiesh (1947) came to a similar conclusion:

"When the experimental procedure involves not normal reading but a critical examination of printed matter with the attendant requirement for speed and accuracy, the observed (changes in) blink rates usually are inconclusive. This suggests that the severity of the visual task introduces factors which neutralize any changes in rate that might be caused by the experimental variable" (p. 268).

Two caveats need to be entertained. The first involves the period over which blinks have to be counted to obtain reliable results, and the second deals with the issue of individual differences in blink rate. From Tinker's (1945) reliability study (of blink rate), it is readily apparent that we should consider a 5-minute period as adequate for obtaining a reliable estimate of blink rate (under a specified condition) during reading. His correlations between successive 5-minute periods range between 0.75 and 0.93. These seem to be adequate for most purposes. When the time sample is extended to 10 minutes, the correlations do not increase; in fact they are generally slightly lower than those for adjacent 5-minute periods. This suggests that other variables become important when we extend time periods beyond the 5-minute range. As Tinker (1945) demonstrated, the correlations using 5-minute time samples also shrink dramatically when one does not compare adjacent 5-minute periods. For example, correlations between the initial and sixth 5-minute periods drop to 0.50. He interprets this low correlation as follows:

"However, in certain other experiments which involved comparison of blink rates at the beginning and end of an hour of reading, the reliability is apt to be critically low, since blink rates barely reach the minimum reliability requirement at the end of 30 minutes of reading" (p. 422-423).

It is our contention that this decrease in the value of the coefficient of correlation does not reflect a lack of reliability of the blink rate measure. It, rather, reflects the differential effect of TOT across subjects. If we may be so bold as to use Luckiesh's suggestion that blink frequency (under specifiable conditions) reflects "fatigue" processes, we have no qualms about accepting the notion that such "fatigue" processes build up more rapidly in some individuals than in others.

The finding by Tinker that the correlation between adjacent 10-minute segments is no better than, and in many cases less than, for adjacent 5-minute periods, suggests to us that one of the assumptions underlying the use of correlational, and time series analytic procedures, is violated by using the longer time sample. The assumptions violated are 1) stationarity of the time series under investigation for time series analyses, and 2) homoscedasticity for the correlational analysis. Thus, the user of correlational procedures must beware, more is not necessarily better, especially if more is achieved by manipulating the time domain. More, in terms of using more subjects, would be vigorously defended by us.

What evidence is there that blink rate, in situations other than reading may index "fatigue" processes? A favorite technique of researchers interested in "fatigue" effects is to "precondition" subjects so that such effects may appear more rapidly. One such technique involves sleep deprivation prior to task performance; another, the use of drugs that are central nervous system depressants. It is assumed that sleep deprived persons should show TOT effects more rapidly than non-sleep deprived persons. A major study demonstrating the effect of sleep deprivation on flight performance (in a flight simulator), will be reviewed in some detail.

Morris (1984) had subjects fly a 4-hour cross-country mission in a (GAT-1) flight simulator. Portions of the flight involved straight and level flying while other portions required flight maneuvers (such as changing altitude, heading, compensating for wind forces, etc.). Subjects were sleep deprived the night before task performance. All flights were conducted in the early afternoon. Measures of flight performance involving maintenance of the aircraft within specified limits for airspeed, altitude, heading, and vertical velocity were abstracted and then combined into a single measure and used as the criterion measure for defining flight performance. A number of eye blink measures were abstracted, and correlated with the flight performance measures. The measures abstracted

were: blink rate, blink closure duration, incidence of long closure duration blinks, and blink amplitude. Step-wise multiple regression analyses were performed to identify the combination of blink measures, which best predicted performance. Blink amplitude, long closure duration blink rate, and average blink closure duration, in combination, accounted for 61% of the variance (*r* of 0.61). Blink amplitude alone accounted for 36% of the variance, and in combination with long closure blink rate 54% of the variance.

When the task was broken down into segments involving straight and level flight and those involving flight maneuvers, the pattern predictive of error scores was somewhat different for the 2 types of flight situations. For the flight maneuver segments, blink amplitude was again the best single predictor (r = 0.25). In combination with blink rate, it was a better predictor (r= 0.48), and those 2 in combination with long closure duration blink rate the best predictor (r = 0.58). For straight and level flight, only 2 variables contributed significantly to the correlation with the performance measure. Long closure duration blink rate contributed most (r= 0.41) and in combination with blink amplitude accounted for 65% of the variance (r = 0.65).

One can conclude from this study that there are reasonable relationships between alterations in performance, as a function of sleep deprivation, and TOT and alterations in eye blink parameters, and that the relationship is dependent on flight conditions. The variables which discriminate are ones that, in our opinion, demonstrate face validity. The blink amplitude measure, which contributed most to the predictive equation, demonstrated that as blink amplitude decreases, performance errors increase. In observing subjects performing this and other tasks over time, one can see the eyelids becoming "heavy," i.e., the lids become partially closed. Blinks from a partially closed position will be of smaller amplitude than those starting from a fully open position. In the Morris study, long closure duration blinks were so identified if "closure duration" ranged between 300 and 400 milliseconds. Closure duration is measured from the point in time where the lid is half closed during the closing phase of blinking, to the point in time where the lid goes back to approximately the same level during the reopening phase. Closures in excess of 400 milliseconds were not evaluated in that study.

The rate of occurrence of such long closure duration blinks was significantly related to performance deficits as a function of TOT. It is the small amplitude blink that is more likely to be related to long closure duration than large amplitude blinks. From a logical and purely mechanical point of view, one would expect that longer closure durations should be associated with larger amplitude blinks. That was obviously not the case. Thus, to the extent that lowering of the eyelids indexes "fatigue," and long closure duration blinks index the same phenomenon they should be related; and they are!!

That blink rate entered into the predictive equation for the flight maneuver, and not the straight and level flight segments, may be attributed to the fact that flight maneuvers are probably associated with larger amplitude eye, as well as head movements. The greater likelihood of blinks in association with large, rather than with small amplitude saccades, has been documented by Fogarty and Stern (1989). Such blinks are not obligatory; they are most likely to occur when information abstracting requirements associated with gaze shift are minimal. In the Fogarty and Stern study, subjects were required to determine if a peripherally presented letter was different from one presented centrally. Four eccentricities for stimulus presentation were used (15 and 50 degree left and right). Blinks were most likely to occur as gaze shifted from a peripheral display back to the central display (in anticipation of the next trial), and occurred more frequently for 50 degree than 15 degree eccentricities. We believe that the inhibition of blinking as gaze shifts to the peripheral location is an active process, and that fatigue processes are likely to interfere with such inhibition. Since such blink inhibition is more likely to occur under the flight maneuver condition, blink frequency appears to be a reasonable contributor to the predictive equation.

A laboratory study by Lobb and Stern (1986) also sleep deprived subjects for one night and induced, by progressive relaxation techniques, a state of relaxation before starting the experiment. The laboratory task

utilized a Sternberg memory task, in which the auditory presentation of 3 nonsense syllables was followed 5 seconds later by a probe syllable, which was to be judged as either a member or not a member of the set. Subjects were required to depress a key upon hearing the first of the 3 syllables, release that key, and then press one of 2 other keys to indicate whether the test syllable was or was not a member of the original set. Thus, 2 types of errors could be identified. The first type of error: attention errors, involved either not pressing or delayed pressing of the key signaling reception of the auditory stimuli. The second error type: decision errors, involved incorrect responses (false alarms) and reflect either improper coding of the stimulus set, poor retention of the stimulus set, or impaired judgment. Eyelid and eye movements were recorded using video recording procedures. Subjects performed the task continuously for 30 minutes. Seven of 9 subjects generated enough decision errors to allow for an analysis of eye variables associated with such errors. Attentional errors occurred too infrequently to allow for analysis. Eye blinks were evaluated from the videotapes and broken down into a number of components, such as time between blink initiation and incursion of the lid on the pupil (LAP), duration of lid over pupil (LOP), duration between lid over pupil and full closure (LBP), and how long the lid remained closed (LD). Similar measures were identified for the reopening sequence. A number of significant differences between trials associated with decision errors and correct responses emerged. Decision errors occurred more frequently when the lid was partially closed, that is, the blink was initiated with the lid just above the pupil or partially covering the pupil. This effect is analogous to the Morris finding dealing with blink amplitude and performance errors. If an eyelid movement starts from a position just above or encroaching on the pupil it will be of smaller amplitude than if it starts from a fully open position. The nature of the lid closure is different under these 2 conditions in that it takes the lid longer to close from the partially closed condition. Thus, similar to the Morris study where small blinks were associated with long closure durations, we also found smaller amplitude blinks associated with longer closing duration.

Our major concern was with the relationship between correct versus erroneous decisions and the nature of the blink. For blinks that occurred in close proximity (within 1 second) of the decision making process, the LOP measure was significantly shorter when subjects made a correct, as compared to an erroneous, judgment. Thus, both of these studies demonstrate the utility of evaluating aspects of blinking other than frequency, in the assessment (or prediction) of performance errors. With respect to TOT effects as operationally defining "fatigue," it should be pointed out that this definition of fatigue would include variables such as boredom and other motivational variables which, by themselves, could account for performance impairment.

We next review 2 studies dealing with the effects of central nervous system depressants and a larger number dealing with TOT effects directly. Stern, Bremer, and McClure (1974) studied the effect of Valium (a clinically used tranquilizer) on eye blinks and other gaze measures during reading. Subjects were required to read text (for pleasure) immediately prior to s arting a regimen of drug or placebo therapy (5 mg t.i.d.) and again after a week of treatment. All participants were being treated by a psychiatrist for minor symptoms of anxiety, and all participated with the full knowledge that some would be on active medication and others on placebo. Blink closure durations were significantly longer and the frequency of long closure duration blinks were also significantly greater for Valium treated subjects. No differences in blink frequency as a function of TOT were recorded in this study since the reading period was relatively short. We would like to point out that knowledge of being on active medication versus placebo, could not account for our results; subjects performed at chance level with respect to their ability to determine medication effects. In a second study Stern, Beideman, and Chen (1976) evaluated the effect of low doses of alcohol (Blood Alcohol Concentration (BAC) averages of 0.07%) on driving ability as measured in a driving simulator. Subjects were required to drive for two 20-minute periods interrupted only by the time necessary to rewind a film and place a new film into a projector. Subjects drove under both sober and "intoxicated"

conditions. There was a significant increase in blink frequency from film 1 to film 2. The increase was predominantly accounted for by the sober condition. Under the inebriated condition, there was no significant change in blink frequency. Blink frequency was higher during film 1 for the inebriated condition, but the difference between sober and inebriation was not significant. With respect to blink closure duration, there was a significant TOT, as well as a significant alcohol effect. Under the inebriated condition, average blink closure duration was longer, and the increase from film 1 to film 2 was significantly greater than in the sober state (significant interaction). In this study, blinks with a closure duration in excess of 150 milliseconds were considered as long closure duration blinks. Significant differences in the percent of blinks with long closure durations were obtained between the sober and the alcohol condition, as well as between film 1 and film 2. Both of these studies thus demonstrate that blink closure duration discriminates between drug and no drug conditions. TOT effects also were demonstrated. Results further suggest that TOT effects occur more rapidly when central nervous system depressants are administered. A person "under the influence of alcohol" may be able to function effectively for the initial 5 or 10 minutes of task performance, but performance degrades more rapidly after that time period for the inebriated, as compared to the sober condition. Thus, devices that stop a driver from starting a car when under the influence of alcohol may only pick up the extreme instances of drug induced impairment. Evaluating what the eyelid does may be a more sensitive measure of such impairment.

We have conducted a series of studies in which subjects were required to maintain attentional set for 30 to 45 minutes. TOT effects in these studies principally dealt with increases in average blink closure duration (Stern et al., 1984; Bauer et al., 1985; Goldstein et al., 1985).

With respect to blink rate in tasks other than reading, most studies utilizing this measure find an increase in blink rate. Carpenter (1948) had subjects perform the Mackworth clock test, a vigilance task, for 2 hours. He obtained an average increase in blink rate of 43% over the 2 hours. Carpenter presents curves of blink rate for each of the 20 subjects who participated. Only 1 subject demonstrated a decrease in blinking over the 2-hour period, and only 2 had increases that were less than 10% of the initial blink rate. Carpenter concludes that rate of blinking can be used as a criterion of visual efficiency. Haider and Rohmert (1976) evaluated blink rate while subjects drove a truck simulator for 4 hours. They report an 80 to 100% increase in blink rate over the 4-hour period. They concluded with the suggestion that results of their correlational analyses "make blinking rate a possible indicator for activation of willingness to good performance" (p. 137). Pfaff, Fruhstorfer, and Peter (1976) report that in a 3-hour driving task, blink frequency increased from approximately 15 to 40 blinks per minute over the test period. These authors also report an increase in blink duration as a function of TOT. They conclude that, "It should be possible to predict dangerous shifts in the drivers vigilance (from eye blink and eye vergence results)" (p. 362).

Frolov (1990) refers to the "eyelid motor response," which we interpret as referring principally to blinking. He had subjects perform a visual vigilance task for approximately 7 hours. We interpret his results as demonstrating both significant increases in blink frequency as a function of TOT, and a reasonable relationship between missing signals and the eyelid motor response.

A recent study conducted by Stern et al. (1994) evaluated blink rate and a series of other measures as subjects performed a 2-hour vigilance task, the Air Traffic Control simulation task developed by Thackray and Touchstone (1989). This task requires subjects to monitor up to 2 sets of 8 aircraft each as they traverse the assigned air space. Occasionally, an event requiring action on the part of the subject appears. Forty-four such events occur during a 2-hour period. The events requiring action involve the appearance of an unidentified aircraft on the display, loss of altitude information on the part of 1 of the aircraft, or 2 aircraft flying on the same vector at the same altitude. If they are flying toward each other, the response required is different from that when they are flying in the same direction. Blink rate was evaluated for consecutive 5-minute periods after 10, 30, 50, 70, 90, and 110 minutes of task performance. Twenty subjects

participated in this study, with each performing the task on 3 separate days. A significant TOT effect was obtained for blink rate [F (2.71, 48.86) = 8.03, p = .0008]. Average blink rate increased from approximately 12 blinks per minute at the 10-15 minute measurement period to approximately 16 blinks per minute for the last period evaluated. Blink rate thus appears to be a robust measure of TOT or fatigue effects.

As Luckiesh warns, blink rate is affected by variables other than TOT or fatigue effects. It is well documented that blink rates during reading are significantly lower than during non-reading periods. The general findings are of a blink rate of approximately 3-7 blinks per minute during reading and a rate of 15-30 per minute during non-reading periods. We (Stern & Skelly, 1984) demonstrated that the blink rate of a pilot flying an aircraft (flight simulation) was significantly lower than that of the copilot, and that when roles were reversed it was the pilot in control of the aircraft who had the lower blink rate. Gregory (1952) demonstrated differences in blink rate attributable to difficulty of a non-visual tracking task, the more difficult task resulting in lower blink rates. Other variables that have been demonstrated to affect blink rate are performing arithmetic manipulations (Gille et al., 1977), vocalizing vs. quiet solving of arithmetic problems (Schuri & von Cramon, 1981), social vs. nonsocial perceptual tasks (von Cranach et al., 1969), being engaged in discussion vs. listening (von Cramon 1980), induced muscle tension (King & Michels, 1957) to mention but a few.

Our essay ends here. It is, in our opinion, abundantly clear that there are well defined conditions in which TOT effects are reflected in an increase in blink rate. One variable that may interfere with obtaining such effects is the interpolation of rest periods or periods of a different activity between segments of (major) task performance. In the case of reading the interference may be the inclusion of requirements involving manual responses (marking with pencil) or vocal activity. We have presented a modicum of data suggesting that other parameters of blinking, such as blink closure duration, are affected by TOT effects. Time does not permit the exploration of other parameters of the gaze control system responsive to TOT effects. We agree with a number of earlier investigators, such as Katz, Luckiesh, Carpenter, Haider, and Rohmert, to mention but a few, who came to the conclusion that blink rate is a reflector of TOT or fatigue effects.

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